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MULTIFUNCTIONAL STRUCTURE-BATTERY MATERIALS FOR ENHANCED PERFORMANCE IN SMALL UNMANNED AIR VEHICLES

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ABSTRACT

Aircraft design and manufacturing have been in a state of constant technological evolution over the last 100 years. Considerable effort has been focused on improving performance, durability, and reliability, and lowering costs. This is being accomplished today using cutting-edge design methodology that incorporates multidisciplinary design optimization of complex systems in place of older methods that independently optimized local subsystems and iterated between designs to satisfy global design constraints.

Air vehicles are designed to move payload between two points, hence increasing the payload capacity or increasing the flight time endurance or range are important system-level goals in the design process. For winged aircraft, a large percentage of total weight is taken up by the structure (~37%) and fuel (~34%) (Thomas et al., 2002). Decreasing the weight of these subsystems or increasing the fuel weight fraction can improve aircraft performance, and this can be accomplished through structure-power multifunctionality. This abstract reports on the design and use of a multifunctional structure-battery (power) material to increase the flight endurance time of a small electric-propelled unmanned air vehicle (UAV).

Flight endurance time is related, in Eq. (1), to the available battery energy, subsystem weights, and aerodynamic parameters. As can be seen from this equation, modifications in the available battery energy or sub-system weights (structure and battery) will affect system performance. Increases in the flight time are sought through a reduction of redundancy between the structure and battery subsystem materials and functions (shape and power). We can accomplish this by using a multifunctional structure-battery material that stores electrical energy while a carrying part of the mechanical load.

$$En_{time} = \left(\overbrace{\frac{E_B\eta_B}{\underbrace{\left(W_S+W_B+W_{PR}+W_{PL}+W_{SB}\right)^{3/2}}_{\textbf{Subsystem Weights}}}}^{\textbf{Available Battery Energy}} \right) \times \overbrace{\left[\frac{\rho S C_L^3}{2C_D^2}\right]^{1/2}}^{\textbf{Aerodynamics, Geometry, etc.}} \underbrace{\eta_P}_{\textbf{Propeller Efficiency}}. \qquad (1)$$

Two important attributes for structure-battery materials are an **arbitrary shaping capability** and **"moderate" structural performance**. The active cells (anode-separator-cathode) of many battery systems are thin laminate sheets that can be cut and molded into any desired shape. The cells can be stacked and bonded together with or without additional structural materials for mechanical enhancement. The composite laminate system is then "bagged" in a special barrier-layer packaging that contains and maintains the chemical environment and allows for mechanical interfacing with the system structure.

The performance of multifunctional composite materials depends specifically on the constituent amounts, properties and mesoscale morphological arrangements. Thomas & Qidwai (2003) and Qidwai et al. (2002) have extended the "Materials Performance" methodology of Ashby (1999) to rank and optimize the mechanical performance of prismatic

composites in terms of their material properties and cross-section architecture (i.e., geometry and arrangement).

The multifunctional structure-battery systems we have been developing consist of laminated polymer lithium ion (PLI) bicell materials with barrier-layer packaging (Dai-Nippon EP-40). The PLI bicell (Figure 1) uses $LiCoO_2$ particles in the cathode and graphite particles in the anode. The anode and cathode particles are held in layer form by a PVDF+HFP polymer matrix "glue" (~70% by weight), which bonds with the separator layer (Gozdz & Warren, 1998). The bicell is thin (~0.5 mm thick) and capable of arbitrary planar shaping and stacking. Nominal properties include: 3.7 volt discharge; 7.2 mAh/cm^2 charge storage capacity; 0.14 g/cm^2 density; and longitudinal and transverse tensile modulus and yield strengths: 1020 & 240 MPa and 3.9 & 1.1 MPa. Nominal properties for the 0.1 mm thick EP-40 packaging include: 0.013 g/cm^2, and 4390 & 4600 MPa modulus and 16.8 MPa (isotropic) yield strength.

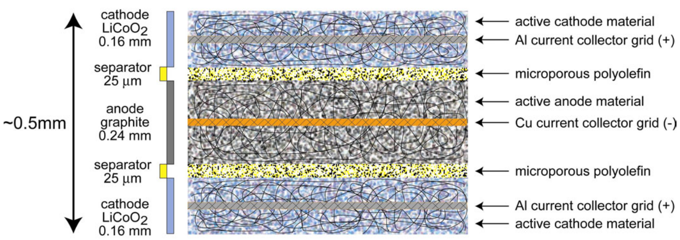

Figure 1: Schematic of the plastic-lithium-ion bicell.

The Wasp (see Figure 2) is a developmental UAV for demonstrating multifunctional structure-battery technology. It is a radio-controlled, "flying-wing" aircraft with a 12.5 inch wingspan. It weighs a total of 171 grams of which 98 grams are structure-battery in the wing. It has achieved a remarkable documented flight endurance time of 1 hour 47 minutes on one charge. The total charge-storage capacity of the structure-battery is 1.8 Ah with an energy density of 136 Wh/kg, an output voltage of ~7.5 V, and an average power output during flight of 9.1 W.

An MDO analysis based on Eq. (1) has been carried out to assess influence of multifunctionality on the flight endurance time. Equal weight designs included in the analysis are the Wasp I (flown), with structure-battery in the upper and lower wing skins, the WASP II (notional), with structure-battery only in the upper wing skin to minimize the fraction of packaging weight, and the Kokam Wasp (notional), a unifunctional design with state-of-the-art commercial polymer-lithium-ion cells. All three of the battery systems are rechargeable. The Kokam cells are slightly better in electrical performance because they use less "polymer glue" in the active layers; the bicell layers are held together by mechanical binding and high-vacuum packaging forces.

The efficiency of the motor/propeller is assumed constant in all three designs because the battery systems have the same output voltage and the total aircraft weights are the same. All of the UAV avionics and shape/geometry parameters were held constant in the analyses. The Kokam Wasp has 20g of weight added to account for structure material added as wing structure and battery containment/carriage.

The important comparison in Figure 2 is that between the Wasp II and the Kokam Wasp, which shows a 9.6% increase in endurance due to multifunctionality. Multifunctional endurance is 25.9% greater than unifunctional endurance if identical specific battery energies are assumed, regardless of the particular value of the specific energy. This would be a significant gain in endurance achieved through multifunctional structure-power. Developing and/or identifying energy storage materials with higher specific energies and arbitrary shaping capability are goals in the ongoing multifunctional materials research effort.

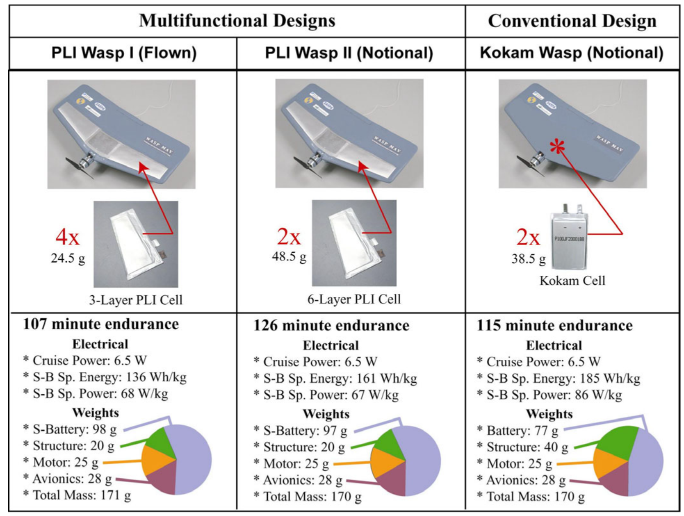

Figure 2: Performance comparison for the Wasp designs.

KEYWORDS: multifunctional composite, structure-battery, unmanned air vehicle, Wasp.

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REFERENCES

Ashby, M.F., *Materials Selection in Mechanical Design*, Butterworth-Heinemann, Oxford, England, 1999.

Gozdz, A.S., and Warren, P.C., "Method for Making Laminated Rechargeable Battery Cells", *US Patent 5,840,087*, November 24, 1998.

Qidwai, M.A., Thomas, J.P., and Matic, P., "Structure-Battery Multifunctional Composite Design", *Proceedings of SPIE*, Paper #4698-19, San Diego, CA, March 2002.

Thomas, J.P., Qidwai, M.A., Matic, P., Everett, R.K., Gozdz, A.S., Keennon, M.T., and Grasmeyer, J., "Multifunctional Structure-plus-Power Concepts", AIAA Paper #2002-1239, AIAA Conference, Denver, CO, April 2002.

Thomas, J.P., and Qidwai, M.A., "Multifunctional Structure-plus-Power Composites", 14th International Conference on Composite Materials; ICCM-14, Society of Manufacturing Engineers, San Diego, CA, July 2003.

